Green Steel

the transition away from carbon

Introduction

Purposes	This publication explores the ways in which steel-making across the world is changing in the face of global warming and climate change. Currently, the global steel industry uses 8% of the world's energy and generates 2.6 gigatonnes (2.6x10^9 tonnes) of CO_2 – 7% of global CO_2 emissions (2020 data). Global steel production continues to grow despite an increase in using recycled steel in the process. This growth will likely persist as many countries across the world continue economic development. Manufacturing steel without huge CO_2 emissions – to produce *green steel* – is an important priority and a great challenge. This resource explores what steel-makers are doing to find low-carbon and zero-carbon routes to steel. The publication is aimed at chemistry and science teachers. It has two purposes: [i] providing an up-to-date picture of industrial steel-making, and [ii] illustrating the work that is being done to reduce and/or eliminate the amount of CO_2 generated.
Acknowledgements	This publication has been funded by Midrex Technologies Inc., an international iron and steel focused engineering and technology company, based in the USA, and we are grateful both for the funding and for information and advice provided during the drafting. We are also grateful to Dr Katherine Aston and Juliette Green for their comments and guidance. The illustrations in the text are used with the permission of copyright-holders identified in the text.
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Part 1 – Reducing carbon dioxide emissions with green steel

Reducing carbon dioxide emissions

Atmospheric carbon dioxide [CO_2] levels went above 400 parts per million [ppm] in 2016 and they have continued to rise with the National Aeronautics and Space Administration [NASA] saying (July 2022) that the concentration had reached 419 ppm. This is the highest level in human history as the last time the Earth saw CO_2 at this concentration was around 4 million years ago when global average temperatures were 4 to 5 degrees Celsius hotter than today, and before humans emerged.

The problem with such CO_2 levels is that they heat up the Earth, its atmosphere and oceans through the enhanced greenhouse effect where energy from the sun is trapped on the Earth's surface by the atmosphere. Because of this, CO_2 is known as a greenhouse gas. Although there are more potent greenhouse gases (methane CH_4 and nitrous oxide NO for example), because of its high concentration in the atmosphere and because it is a stable chemical, CO_2 is the most problematic of these gases.

In 2008, the UK committed to reducing its greenhouse gas emissions by 80% by 2050 compared to 1990 levels. Following recommendations by the Committee on Climate Change, Parliament declared a climate emergency in May 2019 and called on the government to set a more demanding target. It did this in June 2019, by amending the 2008 Climate Change Act to commit to achieving net-zero carbon emissions by 2050. Many now see climate change as one of the biggest threats to the future of humanity. **[1]**

The transition to net-zero

The current transition to this net-zero carbon economy will affect almost every aspect of our lives. Some of these involve everyday choices such as what we eat, the clothes we wear, how we get around, and how our homes are powered and heated. Others are in the background to our lives: unseen but still hugely important. These include how electricity is generated, how transport is powered, how land is fertilised, how communication is enabled, and how vitally important industrial products are manufactured.

Considerable progress has been made in recent years in moving away from fossil fuels to renewable energy sources to generate electricity, but up to now it has been more difficult to make such shifts in other sectors. However, the UN's 2030 Sustainable Development Goals and the 2015 Paris Agreement aim to improve the sustainability of all industrial production and reduce CO_2 emissions to combat climate change.

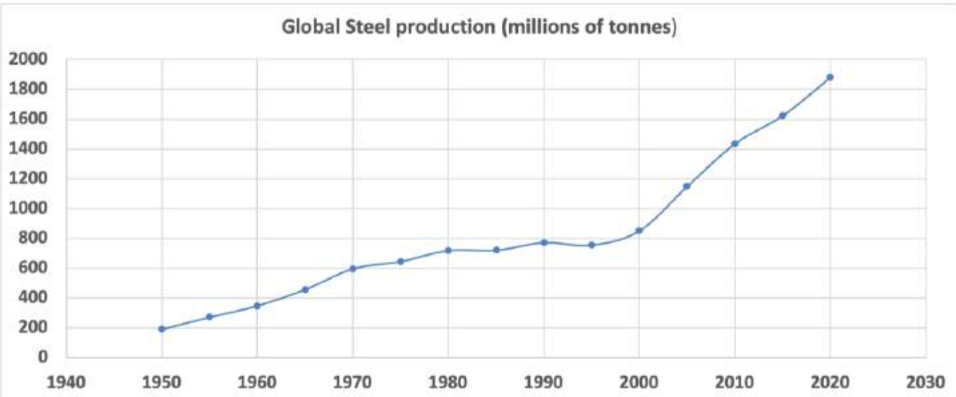
Industrial sources of CO_2

Two of the most significant industrial sectors that need to be decarbonised if we are to reach net-zero are cement and steel-making. Both these processes help power industrial economies as we know them today. **[2]**

Figure 1

World steel production from 1950 (189 tonnes) to 2020.

In 2021 it was 1,951 tonnes.



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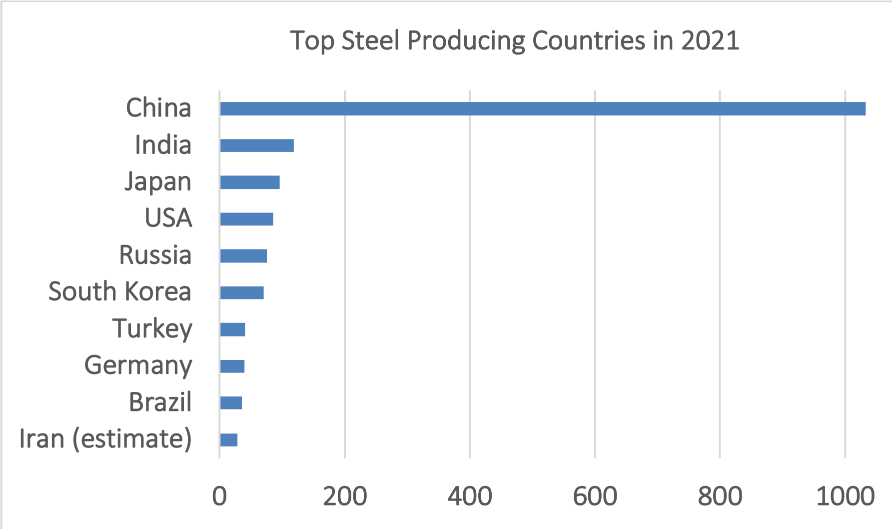
[1] See Note 1
[2] See Note 2

Figure 2

Top 10 steel producing countries in the world in 2021 with China (1032.8 million tonnes) dominating.

By contrast, the UK produced only 7.2 million tonnes.

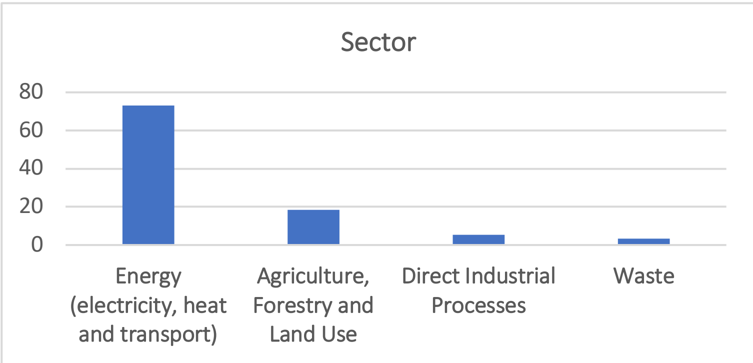


Steel, energy and CO_2

The global steel industry uses 8% of the world's overall energy and generates 2,600 billion tonnes of CO_2. This is 7% of global emissions (2020 figures). The world emits around 50 billion tonnes of greenhouse gases each year [measured in *carbon dioxide equivalents* CO_2eq]. [[3]]

Figure 3

The proportion of global greenhouse gas emissions generated by various sectors (2016 data).



Sources of greenhouse gas emissions

Table 1	Energy Sector [73.2%]	%	Energy Sector [73.2%]	%
The main sources of global greenhouse gas emissions in the Energy sector (2016 data)	Road Transport	11.9	Chemicals / Petrochemicals	3.6
	Residential building uses	10.9	Aviation	1.9
	Iron & steel production	7.2	Shipping	1.7
	Commercial building uses	6.6	Agriculture & Fishing	1.7
	Leakages	5.8	Food and tobacco	1.0

Other industrial processes constitute 10.6% of emissions. [[4]]

Table 2	Agriculture etc [18.4%]	%	Agriculture etc [18.4%]	%
The main sources of emissions generated in the Agriculture, Forestry and Land use sector (2016 data)	Livestock & manure	5.8	Crop land	1.4
	Soils	4.1	Rice cultivation	1.3
	Crop burning	3.5	Grassland	0.1
	Deforestation	2.2		

Steel-making is a carbon-intensive process, and manufacturing it without the huge CO_2 emissions traditionally associated with it – to produce *green steel* – is one of the great challenges we face. This resource explores what is being done to achieve this.

[3] See Note 3

[4] Source of data in Figures 1 to 3 and Tables 1 and 2: Our World in Data: tinyurl.com/3ybj7e4p where explanations of these data will be found

Part 2 – Iron and steel in the curriculum

Context

This resource provides updated information about iron and steel production including the growth of low-carbon alternative methods. Curriculum coverage of iron and steel at the moment is more likely to be found as exemplars of chemical principles rather than features in their own right, and for this reason the resource is aimed at teachers rather than more directly towards students. In doing this, our aim is to support those teachers who already focus their teaching on real-world applications of science and their social and environmental consequences by setting out up-to-date information about iron and steel production. For teachers who currently do less of this, our aim is simply to help them do more. This emphasis on social and environmental issues has grown in recent years and can only become more important as the seriousness of issues around climate change and environmental problems deepen.

Curriculum and examinations

The requirement to study iron and steel, and the social, economic and environmental implications of their production, varies across the UK. In general students will need to know that many metals are extracted from ores, what an alloy is, and about carbon dioxide and the (enhanced) greenhouse effect. In what follows, we give a flavour of what each jurisdiction specifies, and what examination courses cover. This does not set out to be comprehensive.

The GCSE Chemistry specification of the Northern Ireland Council for the Curriculum, Examinations & Assessment (CCEA) has sections that focuses on *metals and the reactivity series* and specifically on *redox, rusting and iron*. Section 2.1.6 says that the curriculum should "examine the relationship between the extraction of a metal from its ore and its position in the reactivity series, for example, iron, a less reactive metal, is extracted by chemical reduction." And section 2.2.5 says that students should be able to "describe the extraction of iron from hematite including the production of the reducing agent, the reduction of hematite; and the removal of acidic impurities." It's also a curriculum aim to develop students' understanding of science on society. In addition, Triple Science students are expected to know about 'green' extraction methods for metals, specifically phytomining.

In Scotland, in Section 3 (Chemistry in Society) of the National 5 chemistry course specification, there is a section focusing on heating with carbon or carbon monoxide (for extraction of Cu, Pb, Sn, Fe and Zn). The guidance says: "National 5 candidates are not required to know the details of the industrial production of iron", but it points teachers to video (and other) resources from the Royal Society of Chemistry which show details of the processes involved. The aims of the course include that candidates should: "develop an understanding of chemistry's role in scientific issues and relevant applications of chemistry, including the impact these could make on society and the environment". This resource addresses these issues directly. **[5]**

For GCSE Chemistry in England and Wales, where most specifications do not require details of the processes of production, students do not need to know any detail about blast or electric arc furnaces, or further refining processes. In the English national curriculum, reference to metal ore reduction is very brief at KS 3 and tends to be treated simply as an example of a chemical reactions with the 'materials' section referring to the use of carbon in obtaining metals from metal oxides. At KS 4, in the 'chemical and allied industries' section, students learn about the extraction and purification of metals related to the position of carbon in a reactivity series, and also about responsible use of natural resources. In addition, Triple Science students are expected to learn about hydrogen as a reductant in the context of fuel cells. This provides a comparison for the reduction of iron using hydrogen

In Wales at KS 4, curriculum specifications say that pupils should have "particular regard to: scientific enquiry, scientific and technological developments, their benefits, drawbacks and risks, and ethical, social, economic and environmental issues and their interaction with science". Students are also expected to

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[5] The Scottish qualifications arrangements can be found at tinyurl.com/5n8fvnp4 with N5 courses being taken in secondary schools (S4 to S6) and in further education colleges.

know about the sustainability of metal extraction processes, including greenhouse emissions and recycling.

With some examination boards there is now an emphasis on ideas such as life-cycle assessments and green chemistry approaches, which fits well with what this resource is focusing on. Taking AQA as an example, the relevant sections of the specification are: 4.4.1.3 Metal extraction, and 4.10 Using resources. Section 4.10 says: "Industries use the Earth's natural resources to manufacture useful products. In order to operate sustainably, chemists seek to minimise the use of limited resources, use of energy, waste and environmental impact in the manufacture of these products." The issues focused on in here directly address these issues.

Table 3 Triple Science Specifications for GCSE Chemistry

Nation [6]	Specification points for Triple Science	Notes
Northern Ireland (CCEA)	2.1.7 recalls that the Earth's resources of metal ores are limited and that alternative extraction methods, such as phytomining, are used.	Also requires specific knowledge about the phytomining process as a 'green' alternative (see 2.1.8)
Wales (based on WJEC)	No additional content.	Both Triple and Double Awards expect learners to know about "factors affecting economic viability and sustainability of extraction processes e.g. siting of plants, fuel and energy costs, greenhouse emissions and recycling" (5.3*l* in Double Award, 2.3q in Triple Science Chemistry).
England	This varies by examination board, but some specifications include industrial chemistry decisions, eg OCR Gateway: "Explain how the commercially used conditions for an industrial process are related to the availability and cost of raw materials and energy supplies, control of equilibrium position and rate" (C6.1f)	Triple Science students also look at fuel cells (e.g. AQA Chem 4.5.2.2, OCR Gateway Chem C6.2q) so are familiar with hydrogen as a reductant.

[6] Scotland does not have the same distinction as other nations between triple and double science. The National 5 Chemistry qualification (used for this resource) is taken by most students in Scotland.

Part 3 – Making steel: using carbon as a reductant

Steel as we know it
In chemical terms, steel is an alloy of iron that contains specific amounts of carbon (usually < 2%) and other metals. All steels contain small amounts of other elements as well as a result of production processes; for example, copper, aluminium, manganese, phosphorus, silicon and sulphur. Steel which has a relatively high proportion of carbon is strong but brittle, while low carbon steels can be shaped more easily. Steels that contain nickel and chromium are known as stainless steel because they resist corrosion.

Further details of steel-making and properties can be found at britannica.com

The American Iron and Steel Institute has a glossary of steel-making terminology on its website, and a flow chart that shows all the different routes into steel and the various fabrication processes in use.

The US National Iron and Steel Heritage Museum's webpages set out how iron and steel are made. [[7]]

According to the World Steel Association, there are now over 3,500 different grades of steel. These have been developed for particular purposes, and have different physical, chemical, and environmental properties. Innovation continues with many modern steels having been developed in the past 20 years. For example, modern cars are built with new steels that are stronger but up to 15% lighter than in the past. [[8]]

Iron
All steel production begins with iron. Iron is the 4th most common element in the Earth's crust (5%) after aluminium (8%), silicon (28%) and oxygen (46%). The history of humans converting ore into iron is a long one starting around the 13th century BCE. Iron is found in nature in an oxidized form, either haematite [Fe_2O_3] or magnetite [Fe_3O_4]. Naturally occurring metallic iron is rare and usually only found in meteorites.

Iron has been so important to the development of human civilisation and culture that we name a period of Earth history after it: the Iron Age. This ran from around 1200 to 500 BCE. Its beginnings marked the points at which bronze tools and weapons were replaced with those of iron. This took place at different times in different places across the world, as the technology spread.

The World Steel Association has an animated timeline of steel productions from its origins in the 13th century BCE to the present day. The National Iron & Steel Heritage Museum in Coatesville, Pennsylvania, has a wide range of videos exploring the human experience of USA steel-making. [[9]]

Iron ore to metal
Historically, carbon has been used as the reductant to remove the oxygen from iron oxide ores. This was originally charcoal (made from wood), then coal or coke (produced from coal). [[10]] Today over 90% of the world's iron is produced as molten pig iron in blast furnaces using coke as the reductant.

The blast furnace was first used in the 14th century, and the processes inside the furnace remain essentially the same today: iron ore, carbon in some form, and limestone react together to produce pig iron. Figure 4 shows this process.

[7] tinyurl.com/3rfp6rn8 / tinyurl.com/2p993czr / tinyurl.com/mpb8usua / tinyurl.com/29hf3mhn
[8] See this World Steel Association article: tinyurl.com/bdeesuav
[9] tinyurl.com/3rfp6rn8 / tinyurl.com/4eph8p35
[10] See Note 4

Figure 4 The Blast Furnace

Raw Materials: crushed iron ore, coke, and limestone.

Powered by: heated air and an exothermic reaction. Hot exhaust gases heat up the air entering the furnace

Product: pig iron often termed 'hot metal'

By-products: calcium silicate slag (used in road building and construction) and exhaust gases (N_2 CO CO_2)

Process: Layers of coke, limestone and ore go in the top of the furnace, and hot air (around 1,100 °C) is blown in from the bottom. The carbon in the coke reacts with oxygen producing carbon monoxide (which is the reductant). This then removes oxygen from the ore to produce metal and CO_2. The actual reactions are more complex than this.

The two reactions raise the temperature to around 1,700 °C, and molten pig iron comes out of the bottom with a carbon content of ~4%. This is then taken to a basic oxygen furnace near the blast furnace.

Silica is separated from the iron as it reacts with calcium oxide (produced by heating the limestone) to form silicates, which float to the surface of the molten pig iron as "slag". The reactions are:

$C + O_2 \rightarrow CO_2$ [exothermic] [11]

$C + CO_2 \rightarrow 2\,CO$ [endothermic]

$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$

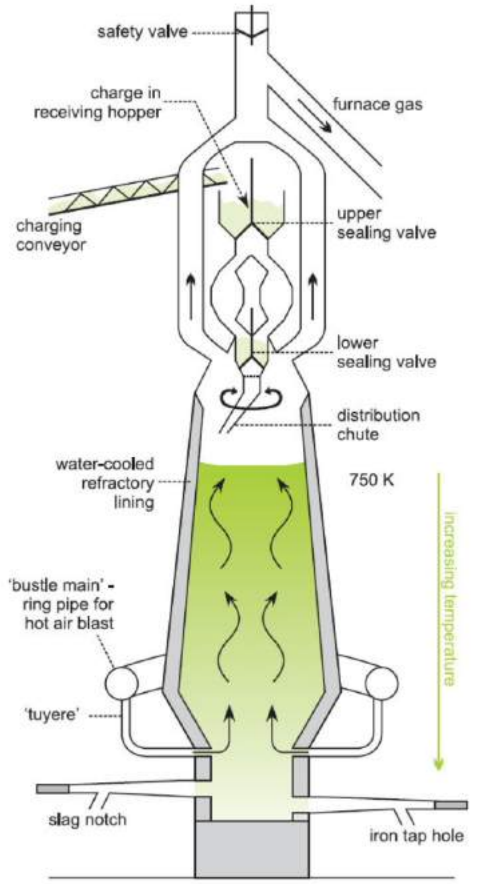


Figure 4 is reproduced, with permission, from *Essential Chemical Industry*, a web site, edited by J N Lazonby and D J Waddington, Department of Chemistry, University of York, UK. [12]

AIST's Steel Wheel [13] is an interactive resource providing video and diagrammatic information about all aspects of steel-making. This provides details of all the traditional steel-making processes set out here.

The use of coal in steel-making accounted for 13.7% of the world's total annual consumption in 2013 (International Energy Agency data). About 80% of this is coking coal used in blast furnaces.

Table 4	Element	%
This shows the composition ranges of different elements in pig iron. The liquid metal (pig iron) coming out of a blast furnace will usually have the range of composition shown here. Pig iron's only use is as an intermediary in the production of other forms of iron (eg cast iron / wrought iron) and in the production of steel	Carbon	3.8 to 4.5
	Silicon	0.4 to 1.2
	Manganese	0.6 to 1.2
	Phosphorus	0.0 to 0.2
	Sulphur	0.0 to 0.04

[11] Tec Science has a detailed view of the exo- and endothermic reactions [tinyurl.com/yzwajz6e] in the blast furnace.
[12] tinyurl.com/48p45yts
[13] tinyurl.com/msckwmd9

There are two large iron and steel plants in the UK at Port Talbot (owned by Tata Steel of India) and Scunthorpe (owned by Jingye of China). At these plants, iron ore is converted into iron and then into steel. Following this, high-tech casting and rolling is used to produce steel shapes that are then made into the final products by customers. [[14]]

A modern blast furnace creates about 1.6 tonnes of CO_2 per tonne of steel produced whereas the global average production is about 2.2 tonnes of CO_2 per tonne because so many old and less efficient blast furnaces remain in use.

Steel makers are also trying to reduce their CO_2 emissions and blast furnaces have used methane injection for some years in order to reduce the coke consumption and try to boost the productivity. Tata Steel in India is using methane extracted from coal mines in the blast furnace process. It is hoped that the trial will provide insights into the operation of blast furnaces with hydrogen-based reductants. [[15]]

Iron to steel

There are two main steel-making methods now in use.

[i] in a basic oxygen furnace using pig iron and scrap steel from a blast furnace
[ii] in electric arc furnace using scrap steel and directly-reduced iron [[16]]

Table 5 shows the big difference between them in CO_2 production (2020 data). These are global figures and there is considerable variation across regions. For example, the share of steel-making in electric arc furnaces is around 42% in Europe and around 67% in North America.

Table 5 [[17]]

Type	Steel (millions of tonnes)	%	CO_2 (millions of tonnes)	%	Tonnes CO_2 per tonne of steel
Blast furnace + basic oxygen furnace	1,346	72	2,961	92	2.2
Electric arc furnace	523	28	209	8	0.4

A third steel-making technology, the open-hearth furnace, is commonly used in India but now only makes up a small proportion of global production. This is now in decline because it is energy-intensive and slow, and therefore costly. Electric arc furnaces spread widely in the early 1960s. The new electric furnaces could produce 110 tonnes of steel in around 3 hours instead of the 10 -12 hours taken in the old open hearths.

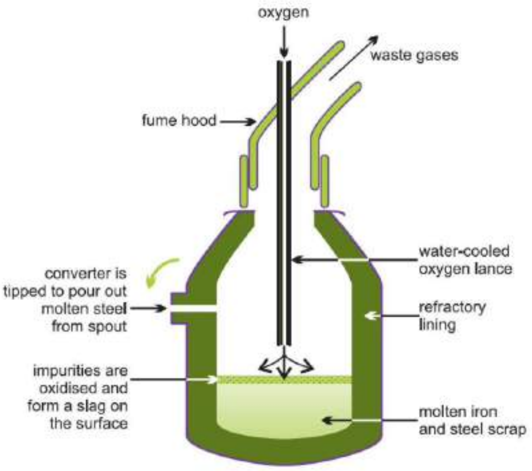
Table 6	**Method**	**%**	**Amount (million tonnes)**
This shows the proportion of steel produced by different methods (2021 data) [[18]]	Blast Furnace / Basic Oxygen Furnace	70.8	1,380.5
	Electric Arc Furnace	28.9	563.5
	Open Hearth Furnace	0.3	65.9
		100	**1,949.9**

[14] UK steel production is 7.2 million tonnes per year which is less than 0.4% of global output. See Figure 2 on page 4.
[15] See Note 5
[16] Directly-reduced iron is the focus of Section 3
[17] Figures taken from S A Hornby Hydrogen-based DRI EASF steelmaking – fact or fiction AIST. International Energy Authority G20 Hydrogen Report: The Future of Hydrogen and Assumptions. S Hornby Evaluating the Viability of H_2 Generated DRI in the EAF; AIST. Australian and New Zealand 2nd annual steel seminar; November 2020.
[18] Source: World Steel Association tinyurl.com/9skew68w

Steel is highly recyclable and most new steel now contains some recycled steel. However, as most steel products remain in use for decades before they are recycled, there is not enough recycled steel to meet world demand. As a result, both main production methods continue to be used. The International Energy Agency thinks that by 2070 the electric arc furnace route will produce more than 70% of world steel.

Although steel is highly recyclable, other elements like copper work their way into the scrap supply. Because of this, the scrap is slowly being contaminated, and that is why we need new iron being produced in order to produce the highest qualities of steel.

Figure 5 The Basic Oxygen Furnace



This is a low-cost process, as no fuel or electricity (other than to produce the oxygen) is needed, and it only takes about 45 minutes.

It does not enable full control over the chemical composition of the finished steel. If this is needed, a ladle refining furnace can be used.

Raw Materials: molten pig iron from a blast furnace (75%), recycled steel (25%) with some flux (limestone)

Powered by exothermic reactions in the furnace

Product: steel

By-products: calcium silicate slag

Process: High-pressure oxygen is blown through a water-cooled pipe (called a lance) onto the surface of the molten mixture in the furnace. This reacts with the carbon to produce CO_2, and with silicon to produce SiO_2. The silica combines with the limestone to form slag, and also oxidizes other impurities present.

When the carbon content is reduced from ~4% to ≤ 0.9% the process is complete and the molten steel is poured off into a ladle which is taken to the refining furnace. More slag is added and a roof with three graphite electrodes is lowered into the ladle.

Argon is injected into the ladle to mix the steel and slag. This reduces impurities and any metals or alloys are added as needed. When the correct chemical composition and temperature are achieved, the steel is sent on for casting

Figure 6 The Electric Arc Furnace

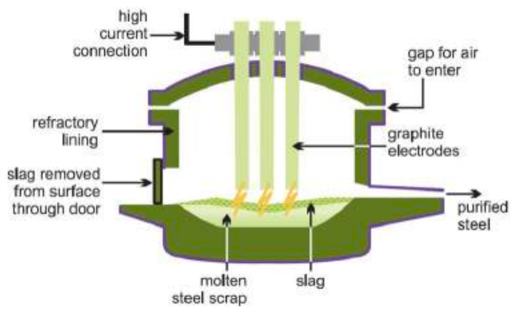
Raw Materials: recycled steel and directly-reduced iron*

Powered by: electricity

Product: molten crude steel which may require ladle refining (see below) depending on the steel grade needed

Process: electricity is arced between graphite electrodes to produce heat which melts the steel. Oxygen and methane can also be injected into the furnace to aid the process and remove impurities; additional metals and alloys can also be added to achieve the desired chemical composition.

* The direct reduction process will be explored in Part 4.



The furnace is tipped to pour the molten steel into a ladle and taken for further refining in a ladle refining furnace. You can also use pig iron in an electric arc Furnace, and some are also used to process hot metal from the blast furnace (especially in India).

Figures 5 & 6 are reproduced, with permission, from *Essential Chemical Industry* a web site, edited by J N Lazonby and D J Waddington, Department of Chemistry, University of York, UK. [19]

[19] tinyurl.com/3hprfd43

Figure 7 shows the various parts of the iron and steel-making process.

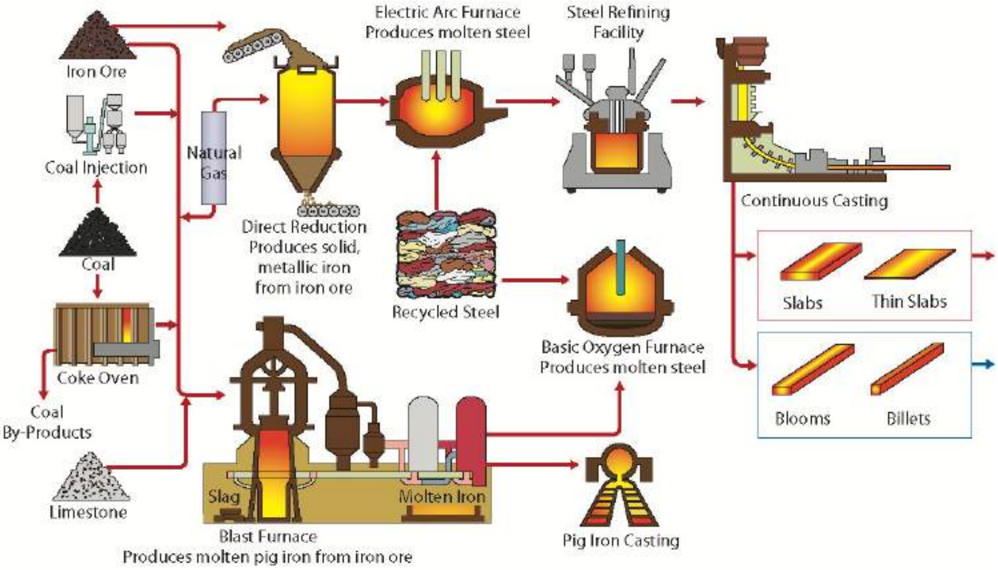


Figure 7 is reproduced, with permission, from the American Iron and Steel Institute. [[20]]

A graphic account of the casting and finishing process can be found in the radio ballad *Song of Steel* by John Tams. This describes working for Steel, Peech and Tozer in Rotherham. [[21]]

[20] An animated version of this can be found on the American Iron and Steel Institute website: tinyurl.com/2tfdsrnb NB, it shows the arrow leading from the basic oxygen furnace to steel refining which is omitted from this diagram.

[21] tinyurl.com/y2uhtv37

Part 4 – Making steel: alternatives to carbon as a reductant

This section explores lower-carbon ways of reducing iron ores to the metal. Steel will always contain carbon; it is not steel if it does not, but this is not a problem that needs to be fixed on our journey to net-zero. The problem that does need a solution is that iron and steel-making processes generate a lot of carbon dioxide. This is because of our reliance on blast furnaces to produce pig iron, and the extensive use of these furnaces across the world.

Direct reduction

Iron and steel production currently creates around 8% [around 3×10^9 tonnes annually] of the world's human-produced CO_2 emissions with over 90% of the world's iron being produced as molten pig iron in blast furnaces using coke as the reductant.

As Table 7 shows just over 6% of iron [as opposed to steel – see Table 6] is produced in a shaft furnace by a process called direct reduction. In this, metallic iron is made from solid iron ore without any melting using carbon monoxide and/or hydrogen as reductants. A very small amount of iron is also made by a process using coal in rotary hearth furnaces (mostly in India).

Table 7 [[22]]

Method	% of iron produced	Method	% of iron produced
Blast Furnace	92.2	Shaft Furnace	6.2

This directly-reduced iron is then most commonly made into steel using electric arc furnaces. It can then be further refined using ladle furnaces in the usual way.

The direct reduction shaft furnace

In the direct reduction process, syngas is the reductant. Syngas is a mixture of hydrogen and carbon monoxide which is produced by reforming methane using a catalyst.

$$CH_4 + H_2O \rightarrow CO + 3\,H_2$$

The hydrogen also participates in the reduction reactions by removing the oxygen from the iron ore with no carbon emission, thus emitting much less CO_2 than a blast furnace.

Figure 8 The Shaft Furnace

Raw Materials: lump or pelletised iron ore

Powered by: Methane or external H_2 or CO

Product: sponge iron (90 to 97% pure)

By-products: CO_2 + H_2O

Process: The shaft furnace is filled from the top with ore. Carbon monoxide and hydrogen are blown into the furnace at temperatures of ~ 1000 °C and percolate up through the ores chemically removing the oxygen in the iron ores to produce metal, steam and CO_2.

$$Fe_2O_3 + 3\,H_2 \rightarrow 2\,Fe + 3\,H_2O$$
$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$$

The resulting iron is porous and can absorb water like a sponge, hence the name of the product: *sponge iron.* This then goes to an electric arc furnace for making into steel.

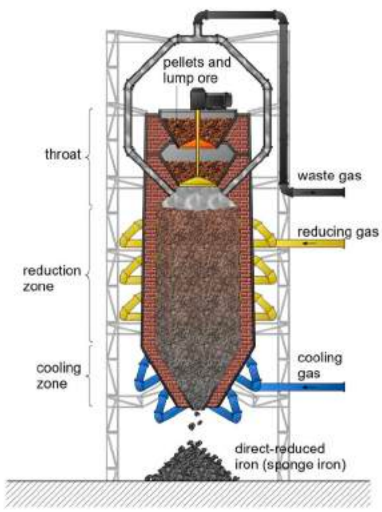


Figure 8 is reproduced, with permission, from Tec-science. [[23]]

[22] Source: World Steel Association: tinyurl.com/4799n6nr
[23] Tec Science: tinyurl.com/tpyb5cuj

Overall, in the conversion of ore to crude steel, this method produces around 50% less carbon dioxide than a blast furnace.

Midrex Technologies, Inc., a US based technology company, built its first direct reduction plant in 1967, and it has now constructed over 90 plants in 22 countries around the world. The Midrex DR technology is responsible for 67% of all directly-reduced iron produced via the shaft furnace method. The total directly-reduced iron produced in the world is around 120 million tonnes a year.

The direct reduction method of converting ore to metal provides a significantly lower carbon alternative route to steel than the blast furnace, as it uses a non-carbon reductant. As we have seen, however, if we start from methane, some CO_2 is still generated. The most desirable reductant, therefore, is hydrogen: providing it is readily available and produced with renewable energy.

Hydrogen

Hydrogen's two main industrial sources are the steam reformation of methane to produce H_2 and CO_2, and the electrolysis of water to form H_2 and O_2. If the electrolysis is done with electricity from renewable fuels, then this is a zero-carbon process. Midrex Technologies is now building a pilot plant in Hamburg for ArcelorMittal that will be complete in 2025. This will be able to use a hydrogen / carbon monoxide mixture or only hydrogen.

This may not necessarily be straightforward as there are technological issues to grapple with. For example:

1. Switching between the two reductants (H_2 or a CO/H_2 mixture) may pose production engineering challenges. For example, when natural gas is used, a layer of carbon forms on the iron's surface which protects it from corrosion. With hydrogen alone, this does not happen.

2. If pure H_2 is used in the shaft furnace then the resulting iron contains no carbon. This is a problem for electric arc furnaces as these need carbon in order to provide energy to help melt the contents. In these circumstances, carbon needs to be added.

3. If the direct reduction process with hydrogen turns out to be more expensive than conventional processes using methane (as seems quite likely), then how are countries to be persuaded to adopt it?

4. Then there is the significant cost of replacing blast furnaces with new technology. It is estimated that the European steel industry would need around $63bn of direct investment to convert blast furnaces and basic oxygen facilities to electric arc furnaces, and an additional $51bn would be needed to set up the supply chain; that is, infrastructure for iron reduction, hydrogen production and storage as well as additional electricity needs of the industry.

How can we obtain the hydrogen for steel production?

Hydrogen can be extracted from fossil fuels, from biomass, or from water. Natural gas (methane) is the main source of hydrogen. It accounts for 75% of the annual hydrogen production [70 million tonnes], and is about 6% of global natural gas use. Depending on its source, varying amounts of CO_2 are also produced.

To distinguish between these sources, and despite its being a colourless gas, hydrogen is given different colour labels to show its origins.

Table 8 shows the eight main colours of hydrogen. [24]

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[24] Data Source: National Grid tinyurl.com/53usdf5c

Table 8

Hydrogen Colour	Source
White	naturally occurring
Grey	fossil fuels: coal & natural gas
Black & Brown	fossil fuels: lignite
Turquoise	methane break up (pyrolysis): $CH_4 \rightarrow C + 2H_2$
Blue	fossil fuels with carbon capture electrolysis of water using non-renewable energy
Green	electrolysis of water using renewable energy
Pink	electrolysis of water using nuclear energy
Yellow	electrolysis of water using solar energy

Recent developments
A Swedish project, HYBRIT—Hydrogen Breakthrough Iron-making Technology—commenced production from a pilot plant in 2021 which is now producing relatively small amounts of steel made without any carbon in the process. The aim of the project is to produce around 1.2 million tonnes of steel annually (about 25% of Sweden's current production). This has the potential to avoid producing 14.3 million tonnes of greenhouse gas emissions over the first ten years of its operation.

A new hydrogen production facility using electrolysis (from renewable electricity) is being built, and the project will enable two blast furnaces to be replaced by an electric arc furnace, using the sponge iron as the feedstock to produce high-quality steel without using coking coal in the reduction step. See Figure 9.

Figure 9 The HYBRIT Process

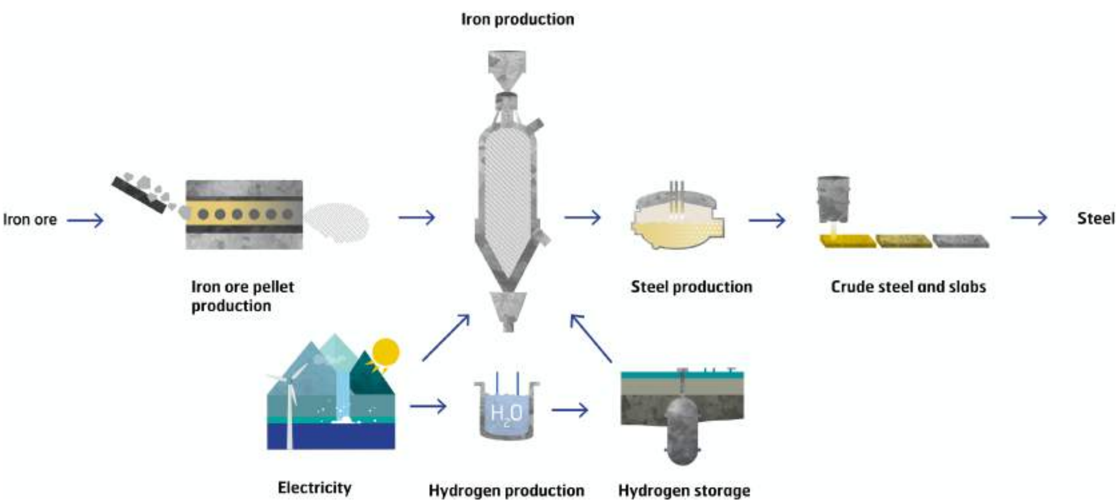

Figure 9 is reproduced, with permission, from SSAB Global Strategic Projects. [25 26]

H2 Green Steel (H2GS AB) was founded in 2020 with the ambition to accelerate the decarbonization of the steel industry using green hydrogen. The founder and largest shareholder of H2 Green Steel is Vargas, which is also co-founder and one of the larger shareholders in Swedish battery maker Northvolt.

[25] SSAB is a steel company with production facilities in Sweden, Finland and the USA [ssab.com]
[26] Here is more detail of the HYBRIT process tinyurl.com/3hcytjed

H2 Green Steel is based in Stockholm, with its first green steel plant under development in Boden, northern Sweden. This new plant build has four components:

- an electrolyser to produce hydrogen,
- a direct reduction plant using this H_2 as the reductant,
- an electric arc furnace and
- a steel mill / casting facility.

One of the key aspects of this project is the ready availability of renewable power in the form of hydroelectricity. With this green hydrogen the plant will be producing 2.5 million tonnes of "green steel" a year by 2026/27.

Will there be enough electricity?
Because the HYBRIT facility is small, there is currently no difficulty in generating enough green hydrogen for it to work. But, the company says that to make a tonne of steel about 2600 kWh of electricity is needed. And when you include the preparation of the ore, the running of the electric-arc furnace, and the steel roller mills, it comes to around 3500 kWh per tonne (3.5 mWh).

Air Liquide is operating a plant in Canada producing 8.2 tonnes of H_2 a day using proton exchange. **[[27]]** This is enough hydrogen to produce 152 tonnes of steel a day by direct reduction in a shaft furnace. This is 2,952 tonnes a year (assuming a 360 day plant operation). Given that the International Energy Agency envisages that by 2050 11.5 million tonnes of H_2 will be needed per year (31,500 tonnes per day) for the steel industry alone, the scale of the challenge is clear.

If we are to replace every blast furnace on the planet and make all steel (all 2 billion tonnes) with green hydrogen, then the amount of electricity needed comes to around 7 x 10^9 mWH (7000 tWh) at the same rate of yearly production. This is about the same amount as all the electricity currently produced from non-carbon sources (wind, solar, nuclear and hydro) across the world. That is to say, we should need to double the amount of non-carbon electricity currently produced to be able to do this – at the same time that as are trying to increase the amount of electricity made from these sources for general usage. If we are to rely only on wind and solar, then we should need to more than double production. And we should also have to rebuild most of the existing steel plants and construct all the electrolysis capacity that will be needed. This suggests that the changeover will occur slowly. **[[28]]**

Other ways forward
Hydrogen gas-based steel-making is not the only way to eliminate carbon, and there are other experimental green-steel production processes.

- In Austria, a project called SuSteel uses hydrogen plasma to melt and reduce iron ore. As it melts, carbon is added to produce steel. This, combines iron-making and steel-making.
- Boston Metal is using molten oxide electrolysis. Here, electricity is passed through melted iron oxide, producing steel at one electrode and oxygen at the other. This is an example of electrowinning.

Steel is already being used more efficiently in building and product production projects, and there is scope for more scrap steel to be used in arc furnaces. This would reduce steel-making's CO_2 contribution from around 7% to <1%.

For a wide-ranging review of the use of alternative carbon sources in electric arc steel-making, see Thomas Echterhof's 2021 review article in the journal, *Metals*: Echterhof, T. Review on the Use of Alternative Carbon Sources in EAF Steelmaking. Metals 2021, 11,222. doi.org/10.3390/met11020222

[27] Science Direct explores this technology tinyurl.com/msh9k4z9
[28] Data source: World Energy Data tinyurl.com/2xfums3a

Inertia in the system

Change is often difficult and expensive. Steel-makers have used blast furnaces for around 200 years so there are a lot of them around and they have been continually refined to optimise production methods and efficiency. If there were not a climate crisis, the calls for replacing the furnaces would be much less strong. But there is, and we do not have another 200 years to make the shift.

Stephen Montague, the CEO of Midrex Technologies, has described the HYBRIT and Midrex processes as *lighthouses*, that will show the way for everyone else. In a 2021 *New Yorker* magazine article he argues that the transition to green steel will not necessarily be quick or easy and that there may well be costs:

> " it's just tough right now. The scale of green hydrogen and its cost is not quite there. The financial community has made it pretty clear that they don't want to lend money to projects that aren't more green. Socially, we've got to be ready to pay something extra. The government can't, frankly, afford to bear the burden of all this themselves. It's going to have to also come down to society appreciating that green steel is a good thing."

Additional costs there may well be, but the transition away from the use of carbon to a greener steel seems inevitable.

Further Reading

A recent article in *The Conversation* by Clare Richardson-Barlow, Andrew Pimm, and Pepa Ambrosio-Albala of the University of Leeds summarises their research on the issues set out here. They conclude that "the UK cannot afford to keep coal-based steelmaking in its decarbonisation strategy and must ensure the steel industry is ready to transition to using green hydrogen fuel instead." [[29]]

[29] High fossil fuel prices mean UK cannot delay transition to low emissions steel tinyurl.com/284sbt36

Part 5 – Notes

1 **Net-zero**
Reducing greenhouse gas emissions to 'net-zero' does not necessarily mean eliminating them completely. It could, for example, mean that some CO_2 continues to be produced but is then captured and stored. The point here is not to add to the CO_2 already in the atmosphere as we are doing now. In the short term this is likely to happen if the capture and storage technology can be made to work at scale. In the longer term, if there is too much CO_2 remaining in the atmosphere, we are likely to need to remove it and be carbon-negative.

2 **Cement & concrete**
Cement is the key ingredient to the production of concrete which provides the basis of most construction projects, and steel is the backbone of construction and engineering and key to the production of machines and consumer goods of all kinds. The 5 billion tonnes of cement produced across the world each year make up 8% of global anthropocentric carbon dioxide (CO_2) emissions. Data source: The Economist (2022) *The wonder material graphene may have found its killer app*. About 1 tonne of CO_2 is created for every tonne of cement made.

To make cement, crushed limestone (calcium carbonate $CaCO_3$) is mixed with clay and heated at over 1,400 degrees Celsius. This process (known as calcination) drives off CO_2. This leaves a residue (called clinker), made up of calcium silicates which is a complex mix of calcium oxide (CaO) and silica (SiO_2). The clinker is cooled and crushed to powder to form cement. Over 50% of the CO_2 emissions created by cement-making occur in the calcination process, with the rest coming from burning fossil fuels to power the quarrying, crushing and transport needed in the process.

The Economist article [[30]] cited above explores a number of possible ways of reducing CO_2 emissions from the cement and concrete production processes, including the use of graphene which would result in the need for less cement, thus reducing CO_2 production. The University of Cambridge has filed a patent for an emissions-free route to cement manufacture. This combines steel and cement recycling in a single process powered by renewable electricity:

3 **CO_2eq**
The idea of carbon dioxide-equivalents is to include all greenhouse gases in order to give a single measure of total emissions, rather than just counting CO_2. To convert non-CO_2 gases into their carbon dioxide-equivalents we multiply their mass by their *global warming potential* (GWP). This measures the warming impacts of a gas compared to CO_2. [[31]]

4 **Coke**
To make coke, coal is powdered and heated to ~1000°C with no oxygen present. As the coal melts all the oils and tars present, together with hydrogen, nitrogen and sulphur are removed. After around 24 hours the coke is cooled and broken into 2cm to 4cm pieces. Coke is porous and hard and between 90 to 93 % carbon. Today, natural gas is increasingly being added in place of coke in blast furnaces to reduce carbon emissions. Pig iron gets its name from the old method of pouring blast furnace liquid into sand moulds. These looked rather like piglets suckling a sow in a sty.

5 **Injecting coal bed methane into a blast furnace**
In early 2022, Tata Steel initiated a trial for continuous injection of coal bed methane (CBM) gas into one of the blast furnaces at its Jamshedpur Works, making it the first such instance in the world where a steel company has used CBM as an injectant. This process is expected to reduce coke use by 10 kg per therm (~0.33 kg per kWh), which will be equivalent to reducing 33 kg of CO_2 per tonne of crude steel produced. Currently the total is around 1,400 tonnes of CO_2 per tonne of steel. Thus, the reduction will amounts to less than 2.5% of the total. [[32]]

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[30] tinyurl.com/mr2em4rd
[31] See Our World in Data tinyurl.com/mr2em4rd
[32] See tinyurl.com/mry6b598

The National Association for Environmental Education – NAEE

Young People benefitting from a field visit sponsored by NAEE through its Kenrick bursary scheme. Image credit NAEE

NAEE is the UK's oldest educational charity supporting schools and teachers to help young people understand the inter-relationship between humans and the rest of nature, and the responsibilities that we have towards the planet. Ours is a long-standing and trusted voice and we recently celebrated our 50th anniversary year. Uniquely, NAEE still produces a termly journal for practitioners. We work with like-minded organisations to promote real-world learning, innovative practice and sustainable school development. We publish blogs, articles, reviews, reports and position papers that are freely-available on our website – naee.org.uk

NAEE is an Incorporated Charitable Organisation [Charity No. 1166502] that is run by its members and volunteers who care passionately about environmental education. Our charitable object is to provide a public benefit by advancing environmental education within early years settings, primary and secondary schools, and institutions responsible for teacher education within the UK and elsewhere by:

1. facilitating curriculum development through the provision of resources, information and ideas for teachers,
2. providing financial support for pupils to visit outdoor education centres, and
3. collaborating with organisations that have related objectives.

NAEE's purpose is to promote all forms of environmental education, and to support all those involved in its delivery, so that together we can understand and act on the need to live more sustainably in order to protect the future of our planet. We believe that young people have a right to first-hand educational experiences in their local environment, because these are critical in helping people understand the importance of the biosphere to all life on the planet, as well as being a source of wellbeing and fulfilment, and a motivation towards sustainable living. The Association is committed to campaigning for a strong focus on environmental and sustainability issues across the school curriculum and supports the work of Teach the Future.

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NAEE – naee.org.uk – can be contacted at info@naee.org.uk